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Strong-gravity effects acting on polarization from orbiting spots

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Abstract

Accretion onto black holes often proceeds via an accretion disc or a temporary disc-like pattern. Variability features, observed in the light curves of such objects, and theoretical models of accretion flows suggest that accretion discs are inhomogeneous and non-axisymmetric. Fast orbital motion of the individual clumps can modulate the observed signal. If the emission from these clumps is partially polarized, which is likely the case, then rapid polarization changes of the observed signal are expected as a result of general relativity effects.

1.1 Introduction

Polarization of light originating from different regions of a black hole accretion disc and detected by a distant observer is influenced by strong gravitational field near a central black hole. A 'spotted' accretion disc is a useful model of an interface of such an inhomogeneous medium, assuming that there is a well defined boundary between the disc interior and the outer, relatively empty but highly curved spacetime. Relativistic corrections to a signal from orbiting spots can lead to large rotation in the plane of observed X-ray polarization. When integrated over an extended surface of the source, this can diminish the observed degree of polarization. Such effects are potentially observable and can be used to distinguish among different models of the source geometry and the radiation mechanisms responsible for the origin of the polarized signal. The polarization features show specific energy and time dependencies which can indicate whether a black hole is present in a compact X-ray source.

Practical implementation of the idea, originally proposed in the late 1970s by Connors et al. (3; 4) and Pinneault (16), is a challenging task because

the polarimetric investigations need a high signal-to-noise ratio. Also, the interpretation of the model results is often very sensitive to the assumptions about the radiation transfer in the source and the geometrical shape and orientation of the emission region. Nevertheless, the technology has achieved significant advances since the 1980s and reached a mature state, as demonstrated also by this Volume. Likewise, numerous theoretical papers have made progress in our understanding of the effects that we should look for. We assume that the gravitational field is described by a rotating black hole, and so the Kerr metric is the right model for the gravitational field.

On the whole, there are some similarities as well as differences between the expected manifestation of GR polarization changes in X-rays and in other spectral bands, such as the infrared region. We will mention these interrelations and point out that the near-infrared polarization measurements of the radiation flares from the immediate vicinity of the horizon are already now available for Sagittarius A* supermassive black hole in the Galactic Center (14; 20).

1.2 Time-varying polarization from orbiting spots

The model of an orbiting bright spot (2; 5; 14; 15) has been fairly successful in explaining the observed modulation of various accreting black hole sources. Certainly not all variability patterns can be explained in this way, however, the scheme is general enough to be able to capture also the effects of spiral waves and similar kind of transient phenomena that are expected to occur in the disc (13; 18; 19). It can be argued that the spot lightcurves can be phenomenologically understood as a region of enhanced emission that performs a co-rotational motion near above the innermost stable circular orbit (ISCO). For example, within the framework of the flare–spot model (6) the spots are just regions of enhanced emission on the disc surface rather than massive clumps that could suffer from fast decay due to shearing motion in the disc. The observed signal is modulated by relativistic effects. According to this idea, Doppler and gravitational lensing influence the observed radiation flux and this can be computed by ray-tracing methods. Such an approach has been extended to compute also strong gravity effects acting on polarization properties (8).

A spot on the disc surface is supposed to be intrinsically polarized (by different possible mechanisms – either by reflection of a primary flare on the disc surface or by synchrotron emission originating from an expanding blob, as detailed below). It represents a rotating surface feature which shares

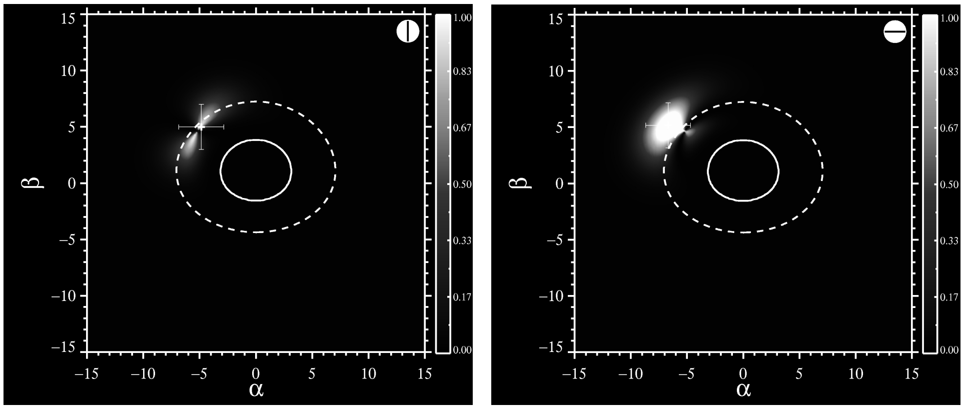

Fig. 1.1. A snapshot of a spot orbiting at constant radius $r = 1.1 r_{\mathrm{ISCO}}$. The image is produced by the spot emission that is assumed to be intrinsically polarized and recorded in two polarization channels, rotated by 90 degrees with respect to each other (21). The direction of the polarization filter is indicated in the top right corner of each of the two panels. The image is shown in the observer plane (α, β), for a non-rotating black hole observed at a moderate view angle, $\theta_{\mathrm{o}} = 45$ deg. The horizon radius (solid curve) and the ISCO (dashed curve) are also shown.

the bulk orbital motion of the underlying medium at sufficiently large radii above the ISCO, gradually decaying due to differential rotation of the disc.

We have applied different prescriptions for the local polarization (see ref. (7; 14; 20) for the detailed description of the model set-up in the individual cases that we investigated). For example, one set of models assumes the local emission to be polarized either in the direction normal to the disc plane, or perpendicular to the toroidal magnetic field. Obviously, in the case of partial local polarization the observed polarization signal will be diluted by an unpolarized fraction, and so the polarization degree of the final signal will be proportionally diminished. In another set of models we assumed a lamp-post illuminated spot as the source of spot polarization by reflection. For the spot shape we first assumed the spot does not change its shape during its orbit, but then we also consider the spot decay with time. The relativistic effects can be clearly identified and understood with these simple (and astrophysically unrealistic) toy models, as they produce visible signatures in the observed polarization properties.

General relativistic effects present in our model can be split into two categories. Firstly, it is the symmetry breaking between the approaching and the receding part of the spot orbit. Doppler beaming as well as the light focusing contribute to the change of the observed flux, especially at high view angles when the spot orbit is seen almost edge-on. Notice that

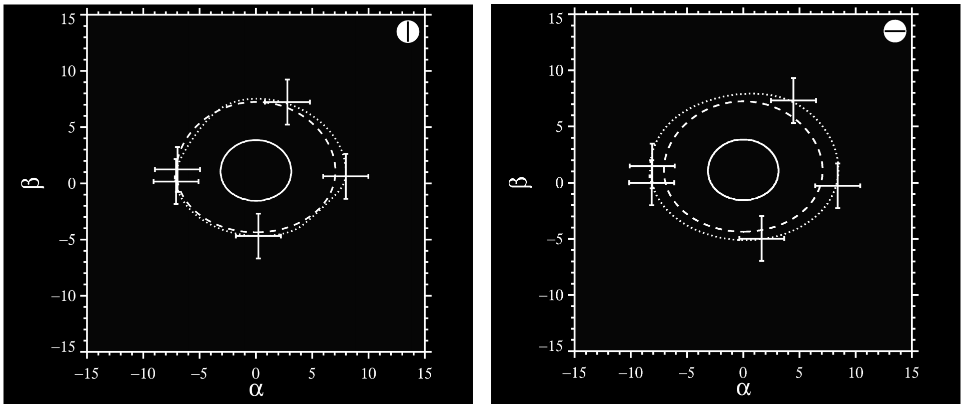

Fig. 1.2. Trajectory of the image centroid during one revolution of the spot corresponding to the previous figure. The wobbling position of the image centroid is indicated by crosses at five different moments along the image track (dotted curve). Figures are courtesy of M. Zamaninasab who has applied the spot model to investigate the polarization properties of near-infrared flares from the Galactic Center supermassive black hole (21).

the Doppler boosting effect is off phase with respect to the light focusing effect, roughly by 0.25 of the full orbit at the corresponding radius. Here, the precise number depends on the black hole spin; it also depends on the inclination through the finite light-travel time from different parts of the spot orbit towards the observer. Also, higher order images could be important in case of almost edge-on view of the spot.

Secondly, rotation of the polarization plane along the photon trajectory also plays a role. This effect is particularly strong for small radii of the spot orbit, in which case a critical point occurs (9). The observed polarization angle exhibits just a small wobbling around its principal direction when the spot radius is above the critical point, whereas it starts turning around the full circle once the radius drops below the critical one. Notice that the exact location of the critical point depends on the black hole angular momentum, in principle allowing us to determine its value.

However, a caveat (and a third point on the list) is caused by sensitivity of the critical radius to the special relativistic aberration effects, especially at small view angles (i.e. when the spot is seen almost along the rotation axis). This means that the moment when the observed polarization angle starts rotating is sensitive to the underlying assumption of a perfectly planar geometry of the disc surface.

By combining the above-mentioned effects together, Dovčiak et al. (7) have shown that the observed polarization degree is expected to decrease

(in all their models) mainly in that part of the orbit where the spot moves close to the region where the photons are emitted perpendicularly to the disc. In this situation the polarization angle changes rapidly. The decrease in the observed polarization degree for the local polarization perpendicular to the toroidal magnetic field happens also in those parts of the orbit where the magnetic field points approximately along light ray.

For the more realistic models the resulting polarization shows a much more complex behaviour. Among persisting features is the peak in polarization degree for the extreme Kerr black hole for large inclinations, caused by the lensing effect at a particular position of the spot in the orbit where the polarization angle is changed. This is not visible in the Schwarzschild case.

The X-ray polarization lightcurves and spectra are still to be taken by future missions, but one may envision even a more challenging goal connected with imaging of the inner regions of accreting black hole sources. Obviously this is a truly distant future: imaging a black hole shadow would require order of ten microsecond angular resolution. However, what might be realistically foreseen is the tracking of the wobbling image centroid that a spot is supposed to produce (12; 21). With the polarimetric resolution, the wobbling could provide an excellent evidence proving the presence of the orbiting feature. See Fig. 1.1 for an example of the expected form of the spot images and the corresponding centroid tracks in a simplified case of a model spot endowed with an intrinsic polarization that remains constant in the co-orbiting frame. This example assumes a spot rotating rigidly at constant radius near above the ISCO. Orientation of the polarization filter is also fixed, as indicated in the top-right corner of the plot. Correspondingly, Fig. 1.2 shows the tracks of the image centroid. Albeit the tracks are not identical in the two orientations of the polarization filter, the difference is rather subtle.

Notice that the project of detecting the centroid motion does not necessarily have to be limited to the X-ray domain. In view of recent results on Sagittarius A* flares, which have been reported in X-rays as well as in the near infrared, submillimiter and the radio spectral bands (1; 10; 11; 17), the immediate vicinity of the black hole can be probed by various techniques. The simultaneous time-dependent measurements equipped with the polarimetric resolution seem to be a final goal of this effort.

1.3 Conclusions

Polarimetry is know to be a photon-hungry technique, and so it is not easy to identify the specific effects of general relativity that could be observed with

available polarimeters (in whatever spectral band) or with those envisaged for realistically foreseeable future. In several recent papers, and in particular in this Volume, various people demonstrate that the task of detecting the relativistic effects and in this way determining the physical parameters of the black hole systems seems to be feasible. Among ways to reach the goal, time-dependent polarization profiles, such as those expected from orbiting spots, play an important role.

It may be worth reminding the reader that the KY code, employed in our computations, is publicly available, either as a part of the XSPEC package or directly from the authors (8). The current version allows the user to include the polarimetric resolution and to compute the observational consequences of strong-gravity effects from a Kerr black hole accretion disc. Within the XSPEC notation, this polarimetric resolution is encoded by a switch defining which of the four Stokes parameters is returned in the photon count array at the moment of the output from the model evaluation. This way one can test and combine various models, and pass the resulting signal through the response matrices of different instruments.

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